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Plasma Convection in the Tail of a Rotating Planetary Magnetosphere

Space Sciences Laboratory
The Ivan A. Getting Laboratories
The Aerospace Corporation
El Segundo, Calif. 90245

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Interim Report

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This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

FOR THE COMMANDER

Jean Bogert

Jean Bogert, 1st Lt, USAF
Technology Plans Division
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Analytical solutions are obtained for the equipotential (E × B) drift trajectories in a certain simplified (but non-dipolar) magnetospheric model. The required superposition of corotation and convection electric fields in the tail leads to drift paths that are concave relative to the earth's dawn meridian. The present model is equally applicable to other planetary magnetospheres having known parameters. For example, the larger magnetic moment and next page

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angular velocity of Jupiter lead to closed equipotential trajectories that lie entirely within the zenomagnetic tail, and thus preclude the adiabatic access of solar-wind plasma to the interior of Jupiter's magnetic tail.

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PREFACE

The author thanks Dr. A. Bratenahl for pointing out prior appearances of the present magnetospheric model in the literature.

CONTENTS

FIGURES

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INTRODUCTION

A standard exercise in magnetospheric plasma physics [e.g., Roederer, 1970] is to calculate the location of the plasmapause and of other equipotential trajectories for a given model of the electric ($\underset{\sim}{E}$) and magnetic ($\underset{\sim}{B}$) fields. Since it is customary to assume that $\underset{\sim}{E} \cdot \underset{\sim}{B} = 0$ and that $\partial \underset{\sim}{E} / \partial t = \underset{\sim}{0}$, one can derive $\underset{\sim}{E} = - \underset{\sim}{\nabla} V$ from the scalar potential $V = V(\alpha, \beta)$, where α and β are the Euler potentials [Stern, 1967, 1971] from which one obtains the magnetic field $\underset{\sim}{B} = (\underset{\sim}{\nabla} \alpha) \underset{\sim}{\times} (\underset{\sim}{\nabla} \beta)$. In other words, the electrostatic potential depends only on coordinates that remain constant along magnetic field lines. Thus, an equipotential trajectory comprises the family of field lines visited by a particle drifting in the direction of $\underset{\sim}{E} \underset{\sim}{\times} \underset{\sim}{B}$.

There have appeared several calculations of such (cold-plasma) drift trajectories, but only the dipolar model of $\underset{\sim}{B}$ [e.g., Alfvén, 1939; Roederer, 1970; Grebowsky, 1970, 1971; Kivelson and Southwood, 1975; Cowley and Ashour-Abdalla, 1976] has thus far yielded analytical expressions for these equipotential trajectories. More realistic models of $\underset{\sim}{B}$ [e.g., Taylor and Hones, 1965; Taylor, 1966; Brice, 1967; Kavanagh et al., 1968] have yielded $\underset{\sim}{E} \underset{\sim}{\times} \underset{\sim}{B}$ trajectories only in the form of numerical output. The purpose of this letter is to report on the analytical calculation of cold-plasma drift trajectories in a certain non-dipolar model of $\underset{\sim}{B}$, i.e., in the field model obtained by superimposing a uniform magnetic field parallel to the magnetic-dipole axis of the planet [e.g., Dungey, 1961; Hill and Rassbach, 1975]. The resulting "magnetosphere" has a tail that is coaxial with the dipole but topologically equivalent to the infinite geomagnetic tail idealized in various magnetospheric models [e.g., Ness, 1969]. Moreover, the present model should apply equally well to the known magnetospheres of other planets.

BASIC EQUATIONS

The magnetic field in the present model is given [Hill and Rassbach, 1975]

$$\underset{\sim}{B} = B_0 a \underset{\sim}{\nabla}[(a/r)^2 \cos\theta - (a/b)^3 (r/a) \cos\theta], \tag{1}$$

where B_0 is the equatorial $(\theta = \pi/2)$ magnitude of the dipolar contribution to $\underset{\sim}{B}$ at the planetary surface $(r = a)$ and b is a constant that ultimately characterizes the magnetospheric diameter. The spherical coordinates r, θ, and φ are measured respectively from the center of the planet, the north pole, and the midnight meridian. The equation of a magnetic-field line is found to be

$$r = [1 + (1/2)(r/b)^3] \, La \sin^2\theta \tag{2}$$

if one requires that $\sin^2\theta \to r/La$ as $r \to 0$. Since (1) is derivable [Stern, 1967] from the Euler potentials

$$\alpha = -(a^2/r) \, B_0 [1 + (1/2)(r/b)^3] \sin^2\theta \tag{3}$$

and $\beta = a\varphi$, the parameter $L\ (\equiv -a B_0/\alpha)$ thus serves as an invariant field-line label.

It follows from (2) that some field lines are open $(L > L^*)$ and some are closed $(L < L^*)$. The configuration is illustrated in Figure 1. The separatrix $(L = L^*)$ can be identified from the property that the direction of $\underset{\sim}{B}$ becomes indeterminate around its equator, which is to say that $\underset{\sim}{B} = \underset{\sim}{0}$ there. Thus, it follows from (1) that the separatrix crosses the equatorial plane $(\theta = \pi/2)$ at $r = b$, whereupon it follows from (2) that $L^* = 2b/3a$.

Open field lines $(L > L^*)$ admit the limit $r \rightarrow \infty$. It follows from (2) for open field lines that

$$\rho \equiv r \sin\theta \rightarrow (2b^3/La)^{1/2} = (3L^*/L)^{1/2}\, b \tag{4}$$

as $z\ (\equiv r \cos\theta)$ approaches infinity. Thus, the magnetospheric diameter $2\rho^*\ (= 2b3^{1/2})$, attained asymptotically as $|z| \rightarrow \infty$, follows at once from (4). The magnetopause corresponds to the boundary $(L = L^*)$ between closed and open field lines. The open field lines in Figure 1 correspond to the tail of the magnetosphere.

The functional form of the electrostatic potential $V(\alpha, \beta) = V(L, \varphi)$ remains to be specified. If the planet's rotation at frequency $\Omega/2\pi$ is coaxial with its "magnetosphere" in the present model, the corresponding φ-independent term in $V(L, \varphi)$ is given [e.g., Schulz, 1970] by $-\Omega a^2 B_0/cL$. No other form is acceptable. The φ-dependent term representing magnetospheric convection must be continuous at

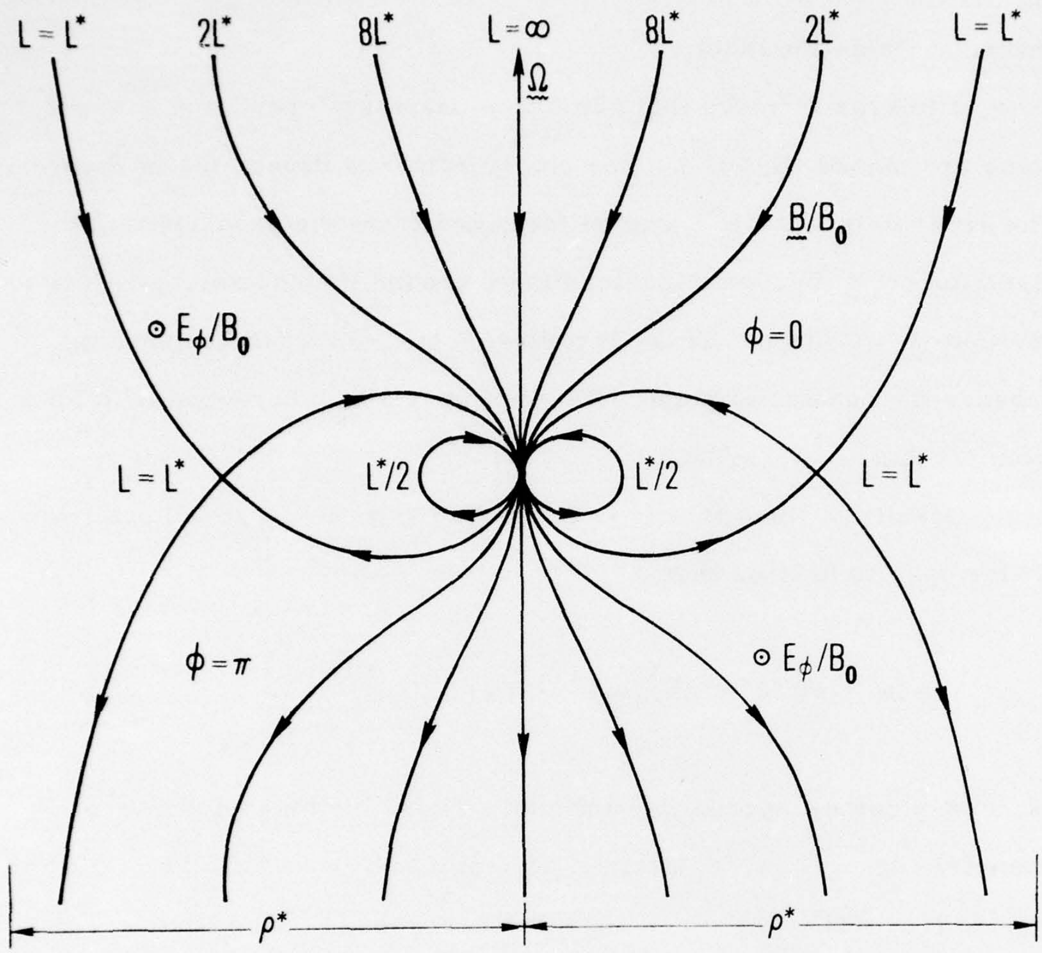

Figure 1. Meridional (noon-midnight) section of magnetospheric model used for mapping $\underset{\sim}{E}$ and $\underset{\sim}{B}$ in the present work [Hill and Rassbach, 1975]. Open field lines correspond to $L > L^*$, and the azimuthal component of $\underset{\sim}{E}/B_0$ is directed as shown.

$L = L^*$. It is convenient to take

$$V(L,\varphi) = E_1 (L/L^*)^n La \sin\varphi - (\Omega a^2 B_0/cL) \tag{5a}$$

(where n is a constant) for $L \leq L^*$ and

$$V(L,\varphi) = (4L^*/9L)^{1/2} E_1 b \sin\varphi - (\Omega a^2 B_0/cL) \tag{5b}$$

for $L \geq L^*$. The first term of (5a) corresponds to an electrostatic potential of the general form postulated by Volland [1975]. The first term of (5b) corresponds to an asymptotically uniform electric field across the magnetospheric tail [Hill and Rassbach, 1975]. This is a special case of the electrostatic potential postulated by Volland [1975] for $L \geq L^*$. However, Volland [1975] assumed a dipolar magnetic field $\mathbf{B}$ and was thus required to introduce an L^* quite arbitrarily in (5). The present discontinuity in $\mathbf{E}$ at $L = L^*$ is an unavoidable consequence of the present magnetic field model, which was introduced by Dungey [1961] and resurrected by Hill and Rassbach [1975].

TAIL CONVECTION PATTERN

Since (4) indicates that $\rho \to (3L^*/L)^{1/2} b$ as $|z| \to \infty$, the quantity $(L^*/L)^{1/2}$ in (5b) should serve as an expedient quasi-radial coordinate in the tail of the magnetosphere. The $\mathbf{E} \times \mathbf{B}$ drift of cold plasma there generates a family of constant-V surfaces that corresponds to a family of coaxial cylinders if $(L^*/L)^{1/2}$ is plotted as a function of φ in polar coordinates. The cylinders have their common axis at

$$(L^*/L)^{1/2} = \left| cE_1 L^{*2}/2\,\Omega\, aB_0 \right| \equiv (1/2)\,(L^*/L_1)^2 \tag{6}$$

on the dawn-dusk meridian. The axis has an invariant longitude $\varphi = (\pi/2)\,\mathrm{sgn}\,(\Omega a/c)$ if (as is assumed here) $E_1/B_0 > 0$. The equation of any such constant-V cylinder is

$$\begin{aligned}[(L^*/L)^{1/2} \sin\varphi \; - (1/2)\,(L^*/L_1)^2\ \mathrm{sgn}\ (\Omega a/c)]^2 \\ + (L^*/L)\cos^2\varphi \; = \; (1/4)\,(L^*/L_1)^4 - (cL^*V/\,\Omega\, a^2 B_0),\end{aligned} \tag{7}$$

and the right-hand side of (7) represents the square of the radius.

If $L_1/L^* > 2^{-1/2}$, then it follows from (6) that the common axis of the drift cylinders must lie within the magnetotail. Sufficiently small drift cylinders in this case will lie entirely on open field lines, and will thus preclude the adiabatic access of solar-wind plasma to their interiors. Drift cylinders that bear labels V such that

$$-(V/E_1L^*a)\,\mathrm{sgn}(\Omega a/c) \quad < \quad (L_1/L^*)^2 - 1 \tag{8}$$

have this property, and the boundary of the adiabatically inaccessible cylinder just grazes the magnetopause at $\varphi = (\pi/2)\,\mathrm{sgn}(\Omega a/c)$.

The foregoing results are illustrated by quantitative example in Figure 2 for three distinct values of L_1/L^*. Magnetotail convection of the correct <u>sense</u>, i.e., from $\cos\varphi < 0$ toward $\cos\varphi > 0$, is

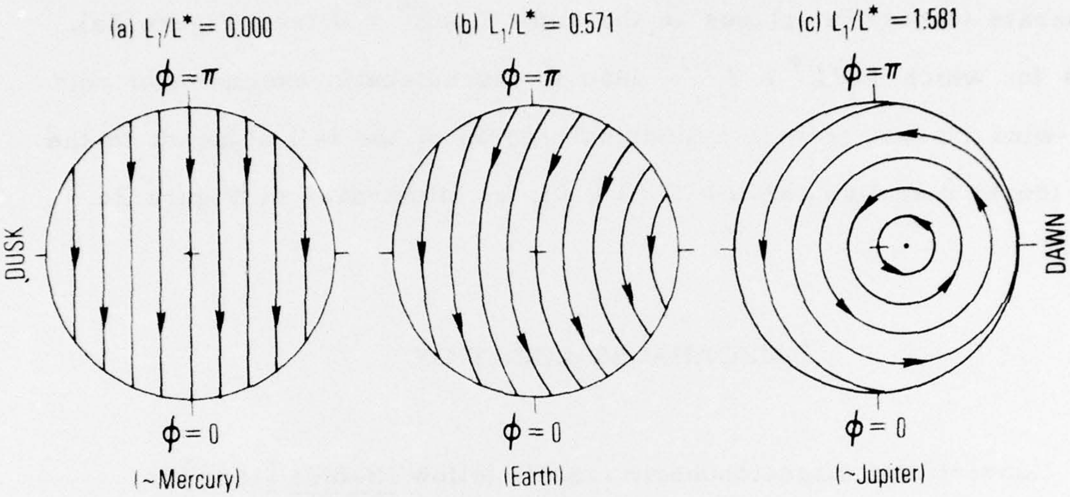

Figure 2. Asymptotic ($z = \pm\infty$) cross sections of the tail of present magnetospheric model showing cold-plasma flow patterns ($\Omega > 0$) for three selected values of L_1/L^*. Radial coordinate: $(L^*/L)^{1/2}$.

assured by the assumption (see above) that $E_1/B_0 > 0$. Cases for which $L_1/L^* < 2^{-1/2}$ provide adiabatic access of cold solar-wind plasma to all the tail field lines, since the corresponding drift shells are partial cylinders (see Figure 2b). The concentric drift cylinders degenerate to parallel planes in the limit $L_1/L^* = 0$ (see Figure 2a). Cases for which $L_1/L^* > 2^{-1/2}$ lead to the adiabatic exclusion of cold solar-wind plasma from a cylindrical region of the tail adjacent to the dawn (dusk) meridian for $\Omega > 0$ ($\Omega < 0$), as illustrated in Figure 2c.

OMEGAPAUSE LOCATION

Conventional magnetospheric models follow Nishida [1966] in identifying the plasmapause as the boundary between closed and open equipotentials of (5a). Such an identification, however, entails no estimate of the actual plasma-density profile (which depends also on the rate of plasma transport along $\mathbf{B}$, for example). Thus, Siscoe and Chen [1975] have suggested "omegapause" as an appropriate name for the boundary between closed and open equipotentials of (5a). The value of V on the omegapause in a given field model is usually found by locating a stagnation point in the equatorial convection pattern, i.e., a closed field line on which $\nabla V \equiv \mathbf{0}$. This corresponds to a field line on which the direction of $\mathbf{E} \times \mathbf{B}$ is ambiguous. It follows from (5a) that the coordinates of this field line must be $\varphi = -(\pi/2)\,\mathrm{sgn}\,(\Omega a/c)$ and

$$L = \left| \Omega a B_0 / c E_1 L^{*2}(n+1) \right|^{1/(n+2)} L^*$$

$$= \left[L_1^2/(n+1)L^{*2} \right]^{1/(n+2)} L^*, \qquad (9)$$

where $L_1 \equiv \left| \Omega a B_0 / c E_1 \right|^{1/2}$ as in (6). If $L_1/L^* < (n+1)^{1/2}$, one obtains the expression [cf. Volland, 1975]

$$(L/L^*)^{n+1} \operatorname{sgn}(\Omega a/c) \sin\varphi =$$

$$(L_1/L^*)^2 (L^*/L) - (n+2)\left[L_1^2/(n+1)L^{*2}\right]^{(n+1)/(n+2)} \qquad (10)$$

for the trajectory of the omegapause. This form allows one to plot φ without difficulty as a function of L/L^*, as in Figure 3b. The omegapause bears the label

$$V = -(n+2) E_1 L^* a \left[L_1^2/(n+1) L^{*2}\right]^{(n+1)/(n+2)} \operatorname{sgn}(\Omega a/c), \qquad (11)$$

which is the value of the electrostatic potential to which it corresponds.

The case $L_1/L^* > (n+1)^{1/2}$ yields no closed field line on which $\underset{\sim}{E} = \underset{\sim}{0}$. In this case the largest closed equipotential surface must be the one that just grazes $L = L^*$ at $\varphi = -(\pi/2) \operatorname{sgn}(\Omega a/c)$. This grazing trajectory bears the label

$$V = -E_1 L^* a \left[1 + (L_1/L^*)^2\right] \operatorname{sgn}(\Omega a/c) \qquad (12)$$

and generates an omegapause profile given by

$$(L/L^*)^{n+1} \operatorname{sgn}(\Omega a/c) \sin\varphi$$

$$= (L_1/L^*)^2 \left[(L^*/L) - 1\right] - 1 \qquad (13)$$

A representative profile of this type is plotted in Figure 3c. Equipotential trajectories exterior to (13) necessarily extend onto open field lines ($L > L^*$) and thus presumably lose their plasma of ionospheric

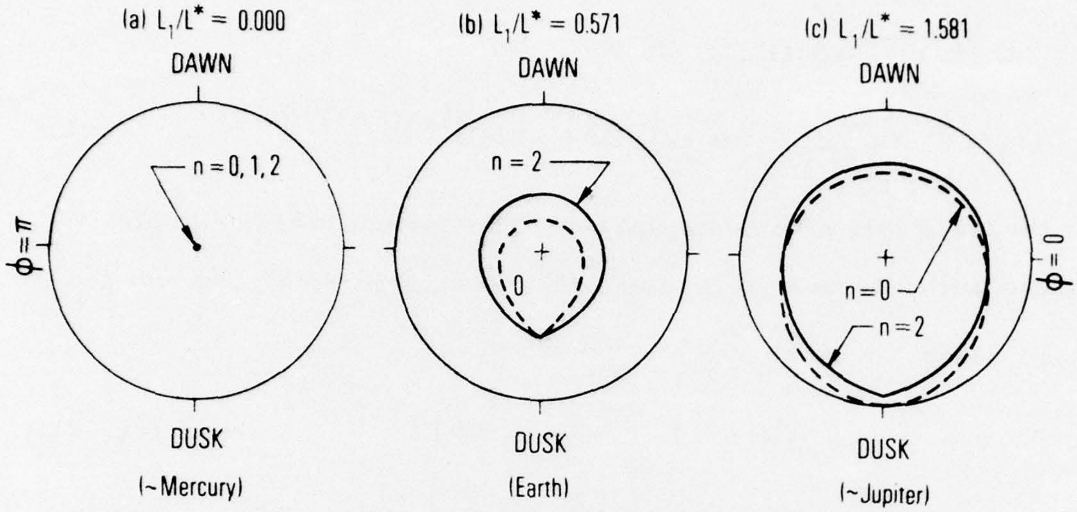

Figure 3. Equatorial ($z = 0$) cross sections of the present magnetospheric model, showing locations of the omegapause for selected values of L_1/L^* and of n. Omegapause is degenerate in (a), the case of a nonrotating planet. Radial coordinate: L/L^*.

origin. Brice and Ioannidis [1970] had qualitatively sketched (for Jupiter) an omegapause that just grazed the magnetopause at dawn. The present equations illustrate such a phenomenon in closed analytical form.

The mathematical condition for having an omegasphere that grazes the magnetopause is $L_1/L^* > (n+1)^{1/2}$. The condition for the magnetospheric tail to contain closed convection trajectories (in the sense of Figure 2c) is $L_1/L^* > 2^{-1/2}$. The similarity of these two conditions makes it unlikely that one of them will be satisfied without the other also being satisfied. Only for $(n+1)^{1/2} > L_1/L^* > 2^{-1/2}$ can there be a cusped omegapause on closed field lines (Figure 3c, solid curve) in the same planetary magnetosphere with open (tail) field lines that are adiabatically isolated (as in Figure 2c) from the magnetospheric surface ($L = L^*$). This transition ($L_1/L^* \approx 0.7$-1.5) between convection-dominated ($L_1/L^* \ll 1$) and rotation-dominated ($L_1/L^* \gg 1$) magnetospheres spans only a factor ~ 2 in L_1/L^* if one takes $n = 1$ as recommended by Volland [1975]. The case of a nonrotating planet (Figures 2a and 3a) corresponds to $L_1/L^* = 0$ and represents an extreme case of the former topology. In this case the omegasphere shrinks to zero radius and disappears beneath the planetary surface.

Application of the foregoing remarks to the plasmapause is contingent on the identification of it with the "last" closed electrostatic equipotential, i.e., with the omegapause, as in Nishida [1966]. Such an identification is contingent on the rate of plasma transport along $\mathbf{B}$, as Siscoe and Chen [1975] have noted. It is also contingent on the lack of plasma transport across equipotentials of (5a). Lemaire [1974, 1975] has strongly challenged this latter assumption on which the identification of the plasmapause with the omegapause is contingent, and has argued that interchange motions driven by the effective gravitational field exert a controlling influence on the shape of the plasmasphere. It would be fair to say (with respect to this issue) that the jury is still out. Thus, it should be emphasized that the criteria on L_1/L^* derived here relate to the shape of the omegasphere and to the magnetotail convection pattern. Whether the inequality between L_1/L^* and $(n + 1)^{1/2}$ ultimately determines the shape of the plasmasphere is a question that remains unanswered in the light of reservations noted above.

INTERPLANETARY SCALING

Insertion of the usual terrestrial parameters ($a = 6371.2$ km, $B_0 = 0.308$ gauss, $E_1 = 0.6$ V/km, $\Omega = 2\pi$ day^{-1}) in (6), with appropriate attention to physical units, yields $L_1 \equiv |\Omega a B_0/cE_1|^{1/2} = 4.877$ irrespective of n. The choice of $L^* = 8.547$ leads to open field lines at all invariant latitudes above 70°, to an asymptotic tail field $B_0(a/b)^3 = 14.76 \times 10^{-5}$ gauss, and to an asymptotic diameter $2\rho^* = 44.37\underline{a}$ for each lobe of the geomagnetic tail. All these parameters are quite reasonable and correspond to a value of 0.571 for the ratio

L_1/L^*. Thus, the earth's magnetosphere corresponds to Figures 2b and 3b.

It would be of great interest in the present context to generate estimates for L_1/L^* in the magnetospheres of Jupiter and Mercury. If calculated from the model of Mendillo and Papagiannis [1971], the parameter $|E_1|$ scales as $(a^3|B_0|R^4)^{-1/6}$ for a constant-velocity solar wind [Schulz, 1975], where R is the distance from the sun. The value of L^* should scale as $(|B_0|R)^{1/3}$, i.e., as the distance from the center of the planet to the magnetopause (measured in planetary radii). Thus, the ratio L_1/L^* should scale as $(\Omega^2|B_0|a^3)^{1/4}$. Insertion of accepted planetary parameters in this scaling law yields $L_1/L^* \sim 10$ for Jupiter and $L_1/L^* \sim 10^{-2}$ for Mercury. The latter result suggests that Mercury (with $L^* \lesssim 2$) has no omegasphere, since it implies that $L_1 \ll 1$. Mercury's magnetosphere must resemble that illustrated in Figures 2a and 3a.

The estimate of $L_1/L^* \sim 10$ suggests that the magnetosphere of Jupiter is a more extreme example of the case illustrated in Figure 2c. For Jupiter the offset cylinder of drift shells adiabatically isolated from the solar wind represents about 99% of the tail volume. The accessible crescent contains only about 1% of the tail volume. Conversely, the oval omegasphere covers about 98% of the equatorial plane of Jupiter's magnetosphere (excluding the tail). The remaining crescent, adiabatically accessible to the solar wind, covers only about 2% of the equatorial area.

The foregoing results suggest that solar-wind plasma has no access to most of Jupiter's magnetotail except by diffusion across the adiabatic ($\mathbf{E} \times \mathbf{B}$) trajectories. This mode of access should be rather inefficient. Thus, the present calculation has shown how the access of solar-wind plasma to most of Jupiter's magnetotail is at least inhibited by planetary rotation. One might conclude, other things (such as $|B_0|a^3$) being equal, that a nonrotating Jupiter would have had a much denser tail plasma. Alternatively, one might look to planets such as Jupiter (with large L_1/L^*) for examples of tail plasma derived largely from the planetary ionosphere [cf. Axford, 1970] rather than from the solar wind.

However, the present results also have major implications for the earth's magnetosphere. Although it is found (see Figure 2b) that solar-wind plasma has adiabatic access to field lines across the entire geomagnetic tail, the adiabatic trajectories themselves show a pronounced curvature in consequence of the earth's rotation. It might be possible to verify this curvature experimentally by tracking the plasma component of a barium cloud released there.

The present calculation applies to an arbitrary planet, with Mercury, Earth, and Jupiter taken as specific examples. The calculation illustrates the importance of superimposing the convection and corotation electric fields throughout the magnetosphere (in the tail as well as on closed field lines). It also emphasizes the operational effectiveness of thinking in terms of $\mathbf{E}$ and $\mathbf{B}$ fields, rather than in terms of "moving" magnetic-field lines. The superposition of convection and corotation electric fields is undoubtedly implicit in the earlier work of Taylor and Hones [1965], but its consequences there are more difficult to identify because the output was purely numerical. The present calculation, based on the magnetospheric model of Hill and Rassbach [1975], enables all the physical boundaries and limiting trajectories to be identified in terms of precise analytical expressions. Of course, the present results would be distorted somewhat in their application to a more realistic magnetosphere, but the basic topology of plasma drift in the tail of a rotating planetary magnetosphere should correspond well to that found here.

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